

HYDROLOGY OF THE PETITCODIAC RIVER BASIN IN NEW BRUNSWICK

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in New Brunswick**

by

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Abstract

Caissie, D. 2000. Hydrology of the Petitcodiac River basin in New Brunswick. Can. Tech. Rep. Fish. Aquat. Sci. 2301: 31p.

The present study quantifies some hydrological characteristics of the Petitcodiac River in New Brunswick. This information is important for many water resource and fisheries studies in the Petitcodiac river basin including the operation of the causeway gates. Long-term hydrologic data such as the mean annual flow and precipitation were calculated and presented. Water loss by evapotranspiration was also estimated using precipitation data and the water loss represents approximately 38% of the total precipitation. A flow duration analysis was conducted and provides estimates on water availability throughout the year and on a monthly basis. Extreme events were analyzed by conducting a low flow and flood flow frequency analysis. Results showed that the magnitude of floods and low flows in the Petitcodiac River were similar to those observed elsewhere in New Brunswick, especially for low return period events (e.g. events that occur on average every 2 years). Ice conditions were also studied and results showed the variability in ice freezeup and breakup conditions. The present study also looked at hydrological data in terms of outliers, independence, and trends in the time series.

Résumé

Caissie, D. 2000. Hydrology of the Petitcodiac River basin in New Brunswick. Can. Tech. Rep. Fish. Aquat. Sci. 2301: 31p.

Cette étude présente les résultats d'une étude hydrologique de la rivière Petitcodiac au Nouveau-Brunswick. Ces informations sont importantes pour l'analyse et la compréhension de projets en ressources hydriques et halieutiques de la rivière Petitcodiac, par exemple l'opération des vannes au pont-chaussée. Les données hydrologiques à long-terme tels que le débit moyen annuel et la précipitation ont été calculées. Les pertes en eau par évapotranspiration ont également été estimées en utilisant les données de précipitation et ces pertes représentent environ 38% de la précipitation totale. Une analyse sur les débits classés a été effectuée afin de fournir de l'information au niveau de la disponibilité en eau sur une base annuelle et mensuelle. Une étude des valeurs extrêmes a été possible par une analyse de fréquence des crues et des étiages. Les résultats de cette analyse démontrèrent que les débits de crue et d'étiage de la rivière Petitcodiac sont semblables à ceux des autres rivières au Nouveau-Brunswick, spécialement pour les débits de faible récurrence (i.e. événements apparaissant en moyenne chaque 2 années). Les conditions de glace de la rivière Petitcodiac ont été étudiées afin de fournir de l'information sur la variabilité du début du couvert de glace et sur la débâcle de la rivière. Cette étude comprend aussi une analyse des données par rapport aux données aberrantes, aux tendances et au niveau de la dépendance des séries chronologiques.

1.0 INTRODUCTION

Hydrological events are important factors in water resource and fisheries management. In particular, streamflow variability and availability can affect stream biota at different life stages during the year. Salmonids can be affected by stream discharge such as high flows by increase mortalities or displacement (Elwood and Waters 1969; Erman et al. 1988). Similarly, low flows can affect fish movement and stream water temperature (Cunjak et al. 1993; Edwards et al. 1979). In order to increase our understanding on streamflow variability and availability in the Petitcodiac River, we carried out a study on the stream hydrology of the drainage basin. Past studies have dealt with ice conditions and river geomorphology below the causeway (Desplanque and Bray 1986, Bray et al. 1982), the current study deals only with the freshwater component of the Petitcodiac River upstream of the causeway.

The objective of this study is to carry out analyses on the hydrology of the Petitcodiac River with the following specific objectives: a) to determine annual flow characteristics of the river (freshwater only), b) to calculate the flow availability through a flow duration analysis, c) to determine the frequency of floods and low flow events, and d) to study river ice conditions using hydrometric data.

2.0 STUDY AREA

This study was conducted in the Petitcodiac River drainage basin located in Southeastern New Brunswick (Figure 1). The drainage basin of the Petitcodiac River has an area of approximately 1360 km² above the Petitcodiac River causeway dam, a tidal control structure which incorporates a major highway crossing connecting the communities of Moncton and Riverview. To study the basin hydrology, discharge data from the Petitcodiac River hydrometric station near Petitcodiac (station 01BU002, A = 391 km²) operated by Environment Canada were used (Environment Canada 1991; Environment Canada 1997). This station has been in operation since 1961, and over 35 years of data were available. To estimate discharge at the causeway, data from this upstream hydrometric station near Petitcodiac were prorated for the total basin using the ratio of drainage basins (factor of 3.5).

3.0 METHODS

The hydrological analysis was carried out using historical hydrometric data from the gauged basin in the study area located near Petitcodiac. Mean annual flow data were used to calculate the mean annual runoff, which is the river discharge expressed in mm. River discharge expressed in mm makes it possible to compare precipitation to runoff data. Daily discharge values were used to conduct a flow duration analysis (i.e. the percentage of time that a specific discharge is equalled or exceeded). These calculations were carried out using computer software (FLODUR; Caissie 1991).

Daily discharge data were also used to calculate high and low flow frequency characteristics for different recurrence intervals (T-year events). Annual flood flows and minimum flows (or low flows) were fitted to statistical distribution functions in a frequency analysis to estimate the T-year events (Kite 1978). For instance, the 25-year ($T = 25$) low flow is one which occurs on the average every 25 years so that 4 such events (of equal or lower magnitude) would have occurred on average in the last 100 years. In the flood frequency analysis, four different models were used (Three-parameter lognormal distribution, Type I extremal (Gumbel) distribution, Log-Pearson type III distribution and a Partial duration series analysis). The first three distribution functions were used to estimate the high flow (T-year) events based on historical annual flood observations (Kite 1978) while the Partial duration series analysis used daily discharge to calculate flood values (Caissie and El-Jabi 1991). In contrast, the Type III extremal distribution was used to estimate the low flow frequency events using daily minimum discharge on an annual basis (Kite 1978).

Various tests were used to observe changes in time series such as flood values or low flows. Dependence in time series occurs when high flow values are followed by high flows low flow values by low flows; otherwise the time series is independent. To study independence in time series, the Wald-Wolfowitz test was used as well as the autocorrelation coefficients of lag 1 and 2 (Bobee and Ashkar 1991; SAS Institute Inc. 1984). Outliers within the data time series (i.e. abnormally high or low values) were identified using the Grubbs and Beck test (Bobee and Ashkar 1991). Also the study of trends was carried out using simple regression analysis. All tests were performed at a level of significance of 95% ($p < 0.05$), except the Grubbs and Beck outlier test which was performed at a level of significance of 90% ($p < 0.10$).

Ice conditions in the Petlocodiac River were studied using the hydrometric gauged data. A *B* symbol indicator is included with the discharge data to identify that the discharge value had been corrected for periods when the hydrometric station was influenced by ice conditions. The presence of the *B* symbol was used as an index of ice conditions or ice cover. This ice condition index was observed in the Petlocodiac River using two approaches. The first approach estimated the duration of ice conditions in days and was obtained by the summation of all *B* indicators during the winter season. In the second approach we identified both the beginning (first date with *B*) and end (last date with *B*) of ice condition in the river. If open water conditions are present in winter, the duration will be less than the difference between the beginning and the end of ice condition.

4.0 RESULTS

The mean annual freshwater flow of the Petlocodiac River at the causeway was calculated at 27.3 m³/s (Table 1). The mean annual runoff shows the unit discharge of the Petlocodiac River (discharge per drainage area) expressed in mm. The mean annual runoff was calculated at approximately 634 mm in a region that receives an average of 1030 mm of precipitation annually (Environment Canada 1987). The difference between precipitation and runoff is the evapotranspiration and was calculated at 396 mm. The ratio of runoff to precipitation is referred to as the runoff coefficient and was calculated at 0.62. This means that 62% of the precipitation in the Petlocodiac River area ends up as water in rivers. The water withdrawal by the city of Moncton at Turtle Creek accounts for approximately 13 mm of runoff per year.

The median flow, which is the discharge available in the river 50 % of the time, was calculated at 11.9 m³/s (or 44% of the mean annual flow). Another flow characteristic of importance is the range of discharge, which was observed to be between 0.36 m³/s and 730 m³/s in Petlocodiac River (Table 1). This informs on extreme events observed within a drainage basin.

A study of the variability in the annual runoff values showed variations between a low of 338 mm in 1985 and a high of 1097 mm in 1979 (Figure 2). The mean annual runoff was calculated at 634

mm (± 174 mm; std). Given the standard deviation of 174 mm, the coefficient of variation was calculated at 0.27 (27%). Although the annual runoff data show periods of high and low values, no trends and cycles were detected in the time series. The annual runoff consisted of an independent time series with a lag 1 and 2 autocorrelation coefficient of only 0.08 and 0.14, which were both insignificant. The 5-year mean shows that long-term values have been highest in the early 1980's and lowest during late 80's (Figure 2).

A flow duration analysis was carried out using daily discharge. Results are shown in percentage ranging from 0% to 100% on a monthly and annual basis (Table 2). The last row in Table 2 shows the mean monthly flows for the Petitcodiac River for comparison with the flow duration analysis. The mean monthly flows ranged from a high value of $85.2 \text{ m}^3/\text{s}$ in April to a low of $7.1 \text{ m}^3/\text{s}$ in September. Low winter monthly flows are observed in January and February at discharges close to $18 \text{ m}^3/\text{s}$. This showed that winter monthly low flows were more than twice those of summer, which occur predominantly in August and September. Therefore the summer low flows in the Petitcodiac River are more severe than the winter low flows.

Monthly median flow (Q_{50} or 50 %) ranged from a high in April of $63.9 \text{ m}^3/\text{s}$ to a low value of $3.2 \text{ m}^3/\text{s}$ in August. Monthly median flow (Q_{50}) can be compared to the mean monthly flows as they both represent a measure of central tendency in occurrence for Q_{50} (where as much data were observed above than below) and central tendency in magnitude for the mean monthly flows. The mean monthly flows were between 1.3 (April and 2.6 (October.) times the median monthly flows (Q_{50} ; Table 2). On an annual basis, the mean annual flow was 2.3 times median flow.

It should be noted that this table shows the range in discharge for each month from the highest observed value at 0% to the lowest at 100%. For instance, the range in discharge observed in June from 1962 to 1997 was from $2.1 \text{ m}^3/\text{s}$ to $228 \text{ m}^3/\text{s}$ (Table 2). Also, the highest daily discharge was observed in April at $730 \text{ m}^3/\text{s}$ while the lowest discharge was observed in both August and September at $0.36 \text{ m}^3/\text{s}$.

The annual flow duration curve shows the distribution of discharge as a function of the percentage of time equalled or exceeded (Figure 3). As an example, for 20 % of the time the Petitcodiac River discharge is above $37.2 \text{ m}^3/\text{s}$ (last column; Table 2). This means that on average, 292 days of the year (80%), the discharge is below $37.2 \text{ m}^3/\text{s}$. Also important in hydrological studies are the low flow characteristics in terms of flow duration analysis, often defined by the Q_{90} and Q_{95} (i.e. 90% and 95% exceedence). For the Petitcodiac River, the annual low flow expressed by Q_{90} was calculated at $2.28 \text{ m}^3/\text{s}$ and the Q_{95} was calculated at $1.60 \text{ m}^3/\text{s}$.

High and low flow frequency analyses were carried out using the Petitcodiac River discharge data. The annual flood series consisted of identifying the maximum daily discharge for each year. The partial duration series analysis makes use of the daily time series of discharges during the same period. The first step was to study the data in terms of homogeneity, independence and trends. Using the Wald-Wolfowitz test, the annual flood data were independent at a level of significance of 95%. A small decreasing trend was detected in the annual flood data ($p = 0.03$) which was due to the high value of 1962 ($730 \text{ m}^3/\text{s}$), however, when this value was removed, the trend became insignificant ($p = 0.16$). Because the 1962 annual flood was not identified as an outlier, the frequency analysis included this value. The low annual flood discharge in 1965 at $104 \text{ m}^3/\text{s}$ was also identified as an outlier (90% significance level) using the Grubbs and Beck outlier test. This annual flood is a low value and the effect of this data point would be minimal on the estimation of high floods, therefore it was also included in the analysis.

The fitting of the flood data was carried out using different distribution functions to determine the frequency of discharge events and to compare among these different distribution functions. Four distribution functions were used for the analysis: the 3 parameter lognormal, Type I Extremal (Gumbel), Log-Pearson Type III and the Partial Duration Series Analysis. The estimated 2-year flood ranged from $290 \text{ m}^3/\text{s}$ to $297 \text{ m}^3/\text{s}$ (Table 3; $T = 2$ years). These results showed that the highest flood value was observed using the 3 parameter lognormal distribution function for low return floods and that this value was very similar to results of other distribution functions. For higher return floods, the Gumbel distribution gave the highest value with a 100-year flood of 688

m³/s. Some flood frequency distributions are more affected by extreme events than others. The annual flood series shows the relation of observed discharge to the fitted model (Figure 4). Each data point represents the maximum annual daily discharge in relation to its cumulative frequency (f) using the Weibull plotting position formula (Chow et al. 1988):

$$[1] \quad f = \frac{m}{n+1}$$

where m refers to the rank of the annual maximum daily discharge in increasing order, and n is the number of years of record. For instance, the highest flood in 35 years of data has a value of $m = 35$ and $n = 35$. Therefore the frequency of such event is $f = 35/36 = 0.972$. Given the frequency (f), the position on the x axis is determined using the Gumbel reduced variable y' :

$$[2] \quad y' = -\ln(-\ln(f))$$

where f is the cumulative frequency calculated by [1]. In the above case with 35 years of data (i.e. $f = 0.972$), the highest flood value has a y' value of 3.56 using [2]. This type of transformation is used for plotting high and low flow data due to the logarithmic nature of these events. Such a plotting transformation is referred to as a Gumbel paper frequency plot.

Most data points or annual floods followed the fitted models except the highest observed value for the Petitcodiac River at 730 m³/s (Figure 4). This discharge was observed in 1962, the first year of hydrometric operation. Given its magnitude it was probably an event in the vicinity of a 100-year flood. As a result of the higher return event of 1962, it was believed that the models with higher predictions (e.g. Gumbel and Log-Pearson Type III) would not necessarily reflect the flood frequency of the Petitcodiac River. Therefore, a mean value among models was used as the better estimate of flood returns for the river. The 2-year event was then calculated at 293 m³/s compared to a 10-year flood event of 457 m³/s. The 100-year event was estimated at 655 m³/s (Table 3; Mean Values).

It is important to note that the three highest annual floods in the Petitcodiac River were observed during the 1960's and included 1963 at $433 \text{ m}^3/\text{s}$, 1967 at $472 \text{ m}^3/\text{s}$ and as mentioned previously 1962 at $729 \text{ m}^3/\text{s}$ (Figure 4). The most recent high flow event occurred in 1987 at $400 \text{ m}^3/\text{s}$ which ranked it 5th.

Index of floods is important as it expresses high return floods as a ratio of the 2-year flood flow event. The index of floods indicates on the slope of the flood curve (where a higher index or ratio represents a more responsive drainage basin to flooding) , and is useful for comparison among rivers. For the Petitcodiac River, the index of floods was calculated at 1.3 for a 5-year event, at 2.0 and 2.2 for the 50-year and 100-year events respectively (Table 3). This means that the 50-year flood for the Petitcodiac River is approximately twice the magnitude of the 2-year flood.

A low flow frequency analysis was also carried out for the Petitcodiac River. In the low flow analysis, annual minimum daily discharge was plotted using the same formula as for high flows (i.e. [1] and [2]) except that low flow ranking was carried out in decreasing order. Before conducting a frequency analysis, data were analysed for outliers and independence. The Wald-Wolfowitz test showed that the time series of minimum annual flows was independent at 95%. No trends were detected in the time series, however, one outlier was present using the Grubbs and Beck test. The outlier identified in minimum flows occurred during the year 1966 with a discharge of $0.36 \text{ m}^3/\text{s}$, the lowest discharge on record. It will ultimately affect the results of the low flow frequency analysis and therefore, the analysis was carried with and without the 1966 low flow.

The model used for low flow frequency analysis was the Type III Extremal distribution function (Kite 1978) and it was observed that the low flow model closely followed the low discharge values recorded for the Petitcodiac River (Figure 5). The 2-year low flow was estimated at approximately $1.5 \text{ m}^3/\text{s}$ while the 5-year low flow was $0.92 \text{ m}^3/\text{s}$ or $0.97 \text{ m}^3/\text{s}$ depending on the inclusion of the 1966 low flow (Table 3). It was noted that the 2-year low flow (at $1.5 \text{ m}^3/\text{s}$, see above) was comparable to the Q_{95} calculated at $1.6 \text{ m}^3/\text{s}$ in the flow duration analysis. This means that the 2-

year low flow is exceeded 95% of time. The 100-year low flow for the Petitcodiac River was estimated at $0.32 \text{ m}^3/\text{s}$. If we exclude the possible outlier (1966) the 100-year event was calculated at $0.44 \text{ m}^3/\text{s}$. The selection of either result in low flow frequency analysis will depend on the problem under investigation. The first and second lowest daily discharges in the Petitcodiac River were observed during the 60's, in 1965 at $0.63 \text{ m}^3/\text{s}$ and in 1966 at $0.35 \text{ m}^3/\text{s}$. The most recent low flow event occurred in 1995 with an observed discharge of $0.67 \text{ m}^3/\text{s}$ ranking it the 3rd lowest in the time series.

The occurrence of peak flows and low flows varies by season. It was observed that in the Petitcodiac River the high flow events occurred mainly from March to May with April having the greatest occurrence of floods with a frequency at 0.38 (38% of the events; Figure 6a). After the spring high flow months, December and July have the next highest occurrence at 0.09 (9%). June can also have annual peak flow events as can the autumn months of October and November. Months without the occurrence of flood peaks during the series (1962-1997) were February, August and September (Figure 6a).

Annual minimum flow occurred mainly during late summer from July to October (Figure 6b). July, August and September are important low flow months with a frequency of 0.21, 0.26 and 0.35 respectively. These three months account for more than 70% of the minimum flow events in the Petitcodiac River. In winter, the only month showing occurrence of annual minimum flow was March with a frequency of 0.9.

Ice conditions in the Petitcodiac River were studied using hydrometric gauged data based on the *B* indicator, which is used by Environment Canada when a station's water level is influenced by ice. It should be noted that unlike discharge data which can be prorated to the whole drainage basin, the ice conditions reported in the present study reflect only the conditions at the location of the hydrometric station near Petitcodiac. Nevertheless, such data are a good indicator of the severity of winters over the years and should provide sufficient information on trends, if they are present. Therefore, in the present analysis, ice influence will be assumed to be the same as ice cover.

The first analysis consisted of quantifying the duration of ice condition over the winter season in days. The duration of ice cover in the Petitcodiac River ranged from 92 days in the winter of 1980/81 to 171 days in the winter of 1971/72 (Figure 7). The mean number of ice covered days in the river was calculated at 124 days (± 16 days; std). No trends were detected in the data ($p = 0.11$), and the time series showed independence at 95% confidence level. An outlier was detected in the season of 1971/72, which means that this particular season was abnormally long in comparison to others.

A study of ice freezeup and breakup was carried out to determine the start and end of ice cover in each winter. The results showed that freezeup (ice cover) occurred between November 6 (day -55; 1973/74) and December 30 (day -1; 1996/97) (Figure 8). The mean value for the ice freezeup was calculated to occur on November 27 (day -34; ± 12 days for std). Similarly, ice out was observed between March 8 (day 67; 1978/79) and April 28 (day 118; 1971/72) with a mean breakup on April 3 (day 93; ± 11 days for std). These results showed that freezeup and breakup have similar variability (i.e. std) at 12 days and 11 days respectively. When studying ice freezeup and breakup, no significant trends were detected ($p = 0.20$ and $p = 0.12$). One outlier was observed during early breakup in 1978/79 with the end of ice conditions on March 8 (day 67; Figure 8). This breakup could be characterised as abnormally early compared to other breakups in the Petitcodiac River

5.0 SUMMARY AND DISCUSSION

Hydrology is an important component in many water resource studies, either because of water management issues or as a result of aquatic and ecological response to flow variability. The objective of the present report was to provide detailed hydrological information on the Petitcodiac River pertaining to annual flow characteristics, flow availability (flow duration), the frequency of high and low flow events, and some ice conditions.

In order to accomplish this, time series were studied for trends, outliers and independence of events. This analysis pointed out abnormal events that occurred in the Petitcodiac River in discharge (both high and low flows) and also in ice conditions during the studied period of over 35 years.

It was observed that the Petitcodiac River has a mean annual flow (MAF) of $27.3 \text{ m}^3/\text{s}$. This flow represents 634 mm of runoff annually in a region that receives approximately 1030 mm of annual precipitation. Therefore, the basin water loss in evapotranspiration was estimated at 396 mm or 38% of precipitation. These results are comparable to other rivers in New Brunswick such as the Miramichi River basin which showed percentage of water loss of 37% (Caissie and El-Jabi 1995). Evapotranspiration was calculated during the calibration period of 1972 to 1978 using data from Dickison et al. 1981, which reflects the hydrology in the Fredericton area (NB). Their data show similar results to the Petitcodiac River with water losses of 31% for Hayden Brook and 38% for Narrows Mountain Brook. The flow duration analysis for the Petitcodiac River showed that the median flow Q_{50} at $11.9 \text{ m}^3/\text{s}$ is close to half the MAF, which is consistent with other New Brunswick rivers.

Floods and low flows were also analyzed for the Petitcodiac River. Flood analysis in the Petitcodiac River showed an abnormally high value of $729 \text{ m}^3/\text{s}$ in 1962, the first year of hydrometric gauge operation, although this discharge was not identified as an outlier at a significance of 95%. This high discharge resulted in the slight downward trend in annual maximum discharge ($p = 0.03$), which becomes insignificant when 1962 data are removed. The 2-year flood was estimated at $293 \text{ m}^3/\text{s}$ for the Petitcodiac River. This value is highly comparable to the low return floods within a similarly sized basin on the Miramichi River watershed. For instance, based on the Renous River data, a 2-year flood of 18.7 mm (equivalent unit area discharge in mm; Caissie and El-Jabi 1995) represents $294 \text{ m}^3/\text{s}$ for a basin the size of the Petitcodiac River. Higher return floods were greater in the Miramichi River. For instance, the 100-year flood was estimated at $655 \text{ m}^3/\text{s}$ for Petitcodiac River compared to $810 \text{ m}^3/\text{s}$ (Renous River, 51.5 mm of equivalent unit area discharge) for a river in the Miramichi basin of similar drainage size. The Miramichi River watershed value represents a 24% increase for the daily discharge value of a 100-

year flood. It should be noted that the estimated 100-year flood for the Petitcodiac River (at $655 \text{ m}^3/\text{s}$) is lower than the value of $950 \text{ m}^3/\text{s}$ calculated in Bray et al. 1982. This is because more data are presently available which makes the high flow of 1962 less important in the frequency analysis (20 years vs. 35 years of data).

Index of flood for Petitcodiac River (Q_T/Q_2) was calculated at 1.3 ($T = 5$ years), 2.0 ($T = 50$ years) and 2.2 ($T = 100$ years). These values are slightly lower than those calculated for the Miramichi River at 1.5 ($T = 5$ years), 2.5 ($T = 50$ years) and 2.8 ($T = 100$ years) (Caissie and El-Jabi 1995). This shows that the flood flows for the Petitcodiac River are less severe than those of the Miramichi River especially for high return floods. This is a function of the flood generation processes (rain and/or rain on snow) as well as geomorphological characteristics such as slopes of river, basin topography, land use and others.

Low flow characteristics for the Petitcodiac River showed different results depending on the inclusion of the low water conditions of 1966, identified as an outlier. The 2-year low flow was close at $1.43 \text{ m}^3/\text{s}$ and $1.46 \text{ m}^3/\text{s}$ depending on the inclusion of the 1966 data (Table 3). A greater difference was observed for the 50-year low flow with discharge of $0.414 \text{ m}^3/\text{s}$ (with 1966) and $0.511 \text{ m}^3/\text{s}$ (without 1966). Generally when comparing among rivers, low flow characteristics are highly variable depending on basin storage such as lakes and swamps and other hydrologic conditions. For instance, unit low flow discharge (discharge per drainage basin area expressed in mm) was estimated at between 0.10 mm and 0.34 mm for a 2-year low flow in the Miramichi River basin (Caissie and El-Jabi 1995) depending on the river studied. The Petitcodiac River 2-year low flow of $1.46 \text{ m}^3/\text{s}$ represents 0.09 mm which is comparable to lower values observed in the Miramichi River basin. The 50-year low flow of between $0.414 \text{ m}^3/\text{s}$ (0.026 mm) and $0.511 \text{ m}^3/\text{s}$ (0.032 mm) for the Petitcodiac River is again within the values observed in the Miramichi River area. Miramichi values ranged between 0.014 mm to 0.104 mm (Caissie and El-Jabi 1995).

Ice cover was the last aspect considered in the Petitcodiac River study. Results showed that on average freezeup occurs close to November 27 and breakup on April 03, with a mean duration of

124 days of ice cover as measured by the presence of ice on the hydrometric station. Only two abnormal events were observed in ice conditions as identified using an outlier test. The first was the 1971/72 winter season during when the duration was abnormally long at 171 days. During this season the latest spring breakup was observed on April 28. The second event occurred during the winter season of 1978/79 with an abnormally early breakup on March 8.

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Table 1. Hydrological characteristics of the Petitcodiac River at the causeway.

Parameters	Magnitude
Drainage basin area	1360 km ²
Median flow	11.9 m ³ /s
Mean annual flow	27.3 m ³ /s
Mean annual runoff	634 mm
Mean annual precipitation	1030 mm
Minimum daily discharge	0.36 m ³ /s
Maximum daily discharge	730 m ³ /s

Table 2. Flow duration analysis (using daily streamflow data) and mean monthly flows of the Petitcodiac River at the causeway. All values are expressed in m³/s.

Percentage (%) ¹	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual ²
0%	414	286	383	730	473	228	302	173	211 ¹	320	369	351	730
10%	31.5	37.5	91.8	178	106	40.5	23.9	15.1	17.4	41.6	66.0	71.3	68.5
20%	21.4	21.2	50.4	129	61.0	24.5	14.2	9.5	8.6	26.4	41.9	40.7	37.2
30%	16.4	14.1	33.4	98.6	45.3	17.5	9.9	6.3	6.0	16.9	30.3	28.4	24.6
40%	12.9	10.7	23.9	78.1	36.2	13.4	7.4	4.2	4.3	10.8	23.4	21.1	16.9
50%	10.7	8.5	17.1	63.9	29.7	10.7	5.6	3.2	3.3	7.2	17.9	16.7	11.9
60%	9.0	7.1	13.0	53.2	25.2	8.8	4.2	2.6	2.7	5.2	13.9	13.6	8.6
70%	7.5	5.9	9.4	43.6	20.2	7.5	3.2	2.1	2.0	3.6	10.1	10.7	6.0
80%	6.1	4.9	6.2	34.0	16.4	5.8	2.6	1.6	1.6	2.6	6.4	7.8	3.9
90%	3.6	3.3	4.3	27.3	12.4	4.3	1.8	1.3	1.2	1.7	4.0	4.1	2.3
95%	2.4	2.6	3.0	18.5	9.8	3.7	1.5	1.0	0.96	1.4	3.0	2.1	1.6
100%	1.7	1.5	1.4	6.6	3.8	2.1	0.79	0.36	0.36	0.71	1.23	0.87	0.36
Mean monthly flows	18.2	17.0	36.2	85.2	46.5	18.8	12.7	7.68	7.10	18.4	29.0	30.6	27.3

¹ Percentage (%) = Percentage of time equalled or exceeded; and ² Mean annual flow.

Table 3. Frequency analysis of the Petitcodiac River at the causeway using different statistical distributions. Discharges of different recurrence interval (T) in years are expressed in m³/s.

Statistical distribution	Flood Frequency Recurrence interval (T) in years					
	2	5	10	20	50	100
Lognormal 3P	294	391	449	503	569	617
Type I Extremal (Gumbel)	290	393	461	526	610	673
Log-Pearson Type III	287	383	448	512	596	661
Partial Duration Series	290	382	442	501	576	632
Mean Values	290	387	450	510	588	646
Index of Floods	1.0	1.3	1.6	1.8	2.0	2.2
Statistical distribution	Low Flow Frequency Recurrence interval (T) in years					
	2	5	10	20	50	100
Type III Extremal (with 1966)	1.43	0.897	0.678	0.536	0.414	0.355
Type III Extremal (without 1966)	1.46	0.949	0.748	0.619	0.511	0.459

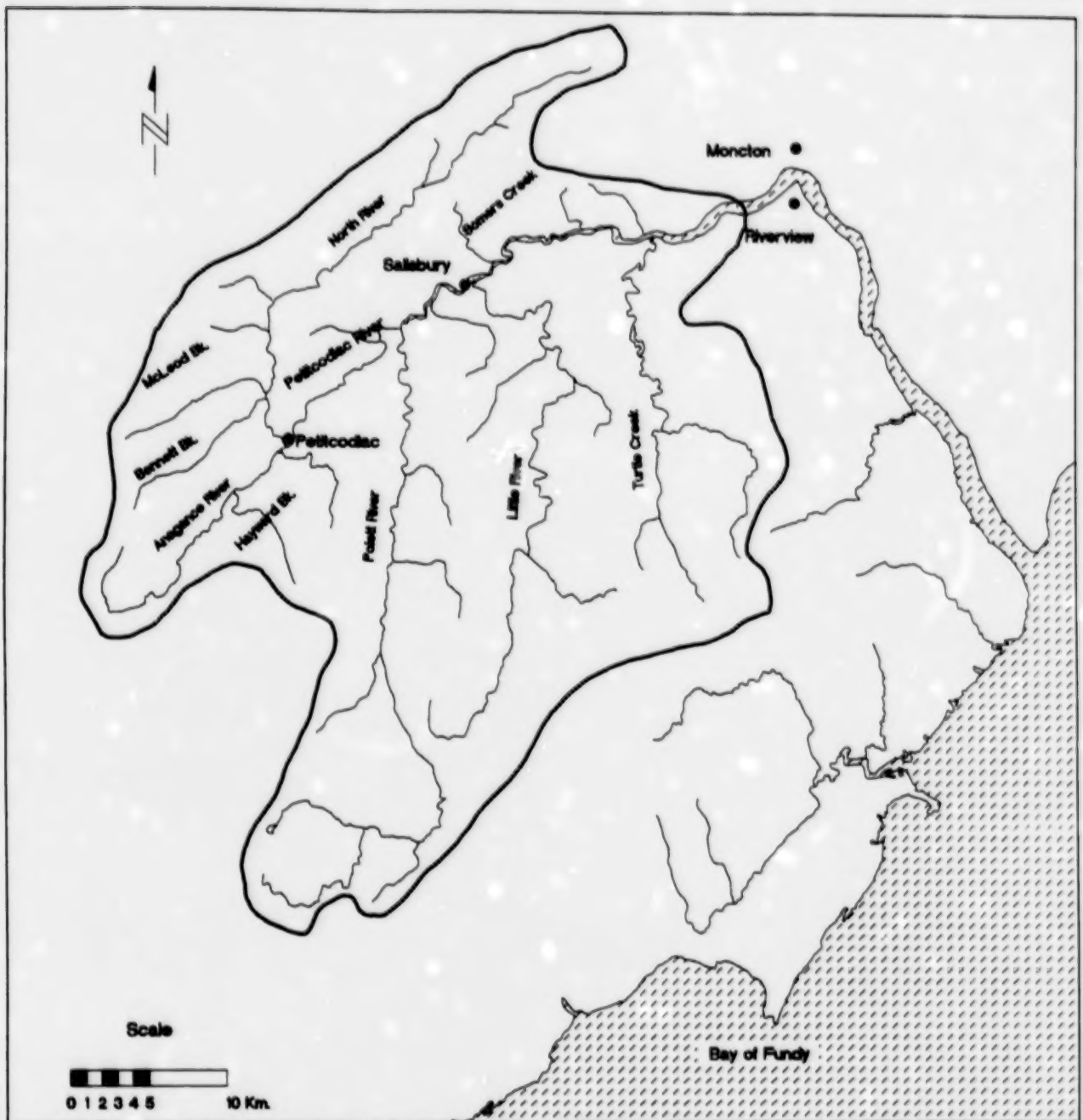


Figure 1. Map of the Petitcodiac River showing the drainage basin above the causeway.

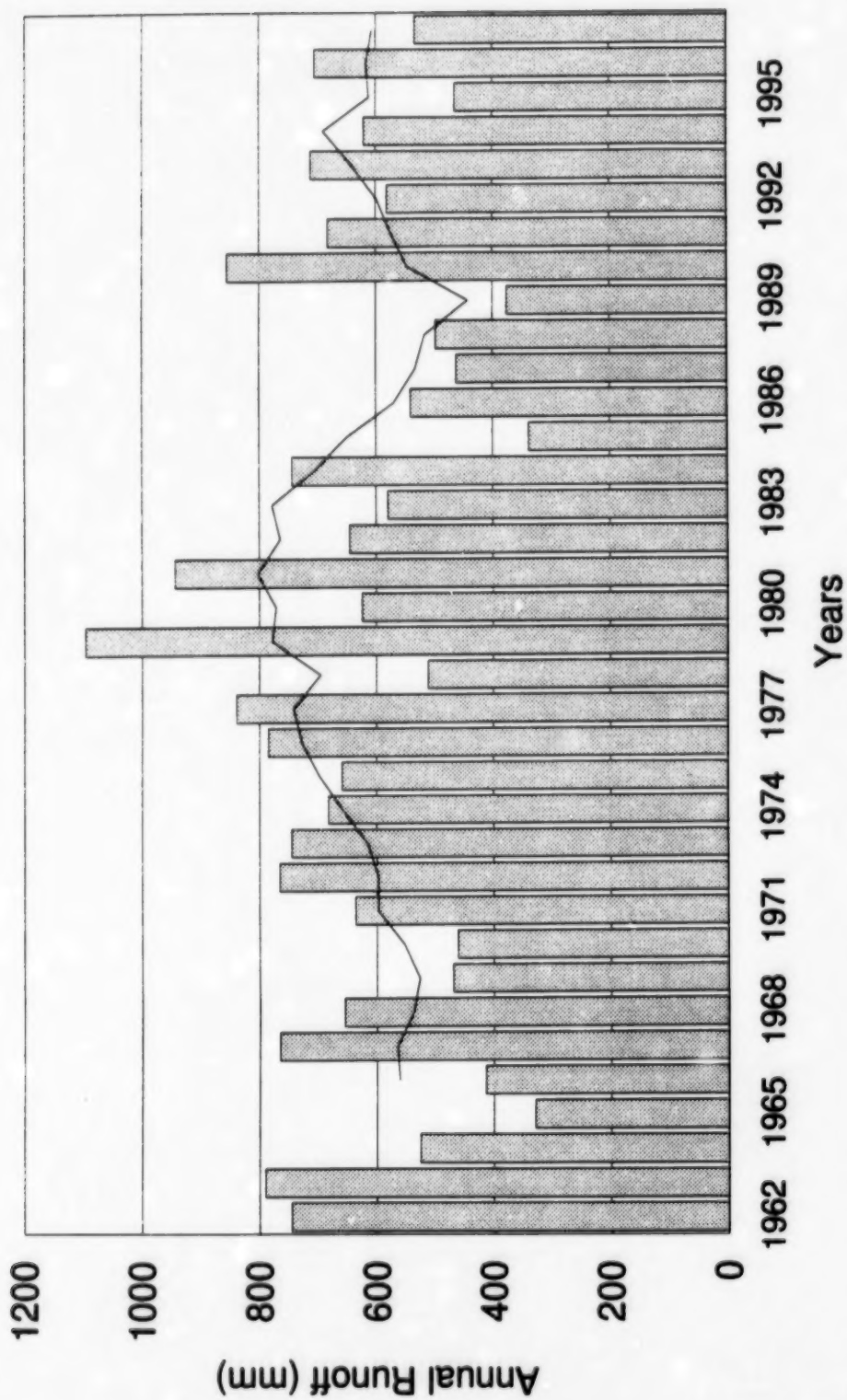


Figure 2. Annual runoff (mm) of the Petitcodiac River (line indicates the 5-year mean).

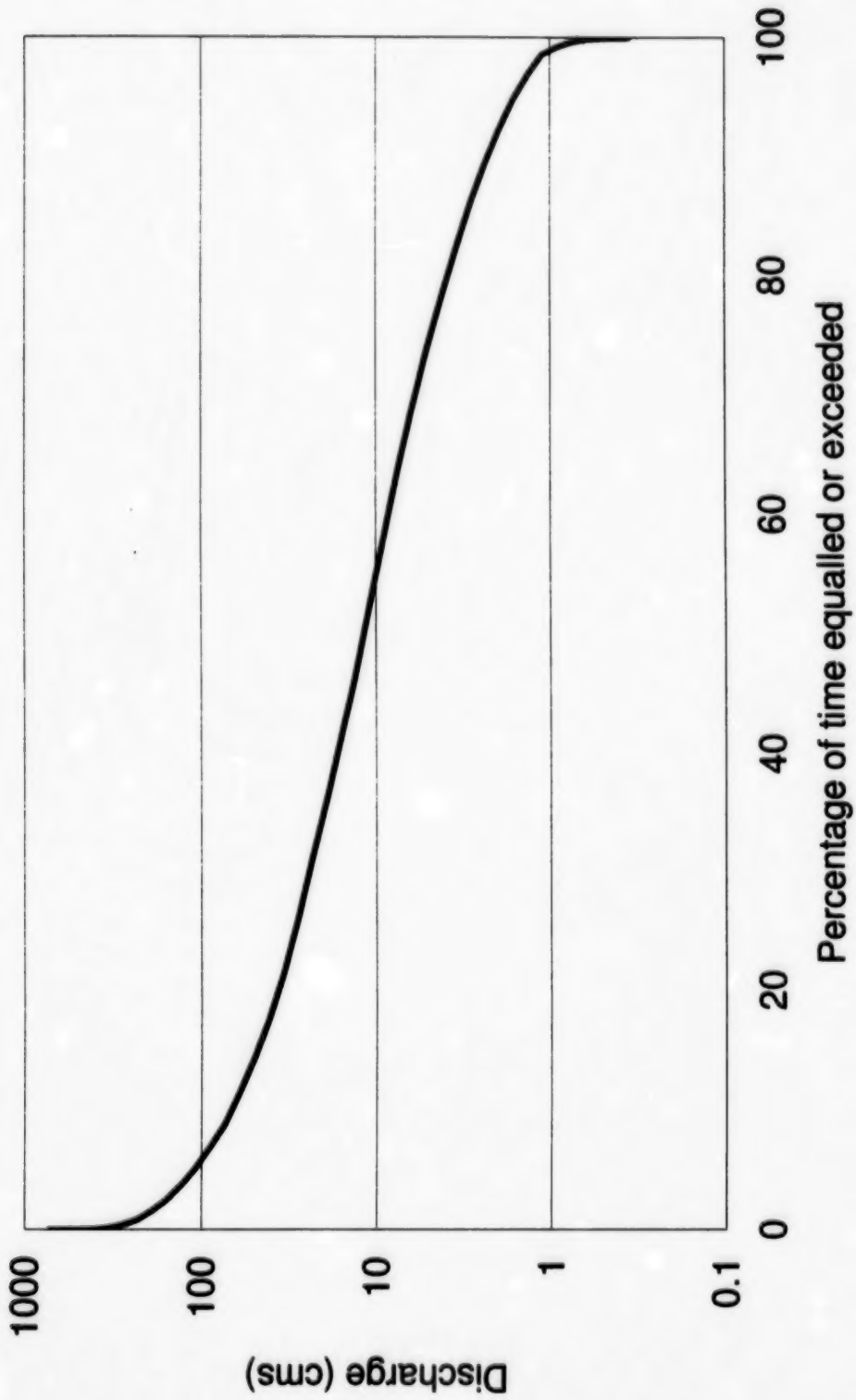


Figure 3. Annual flow duration curve of the Petitcodiac River

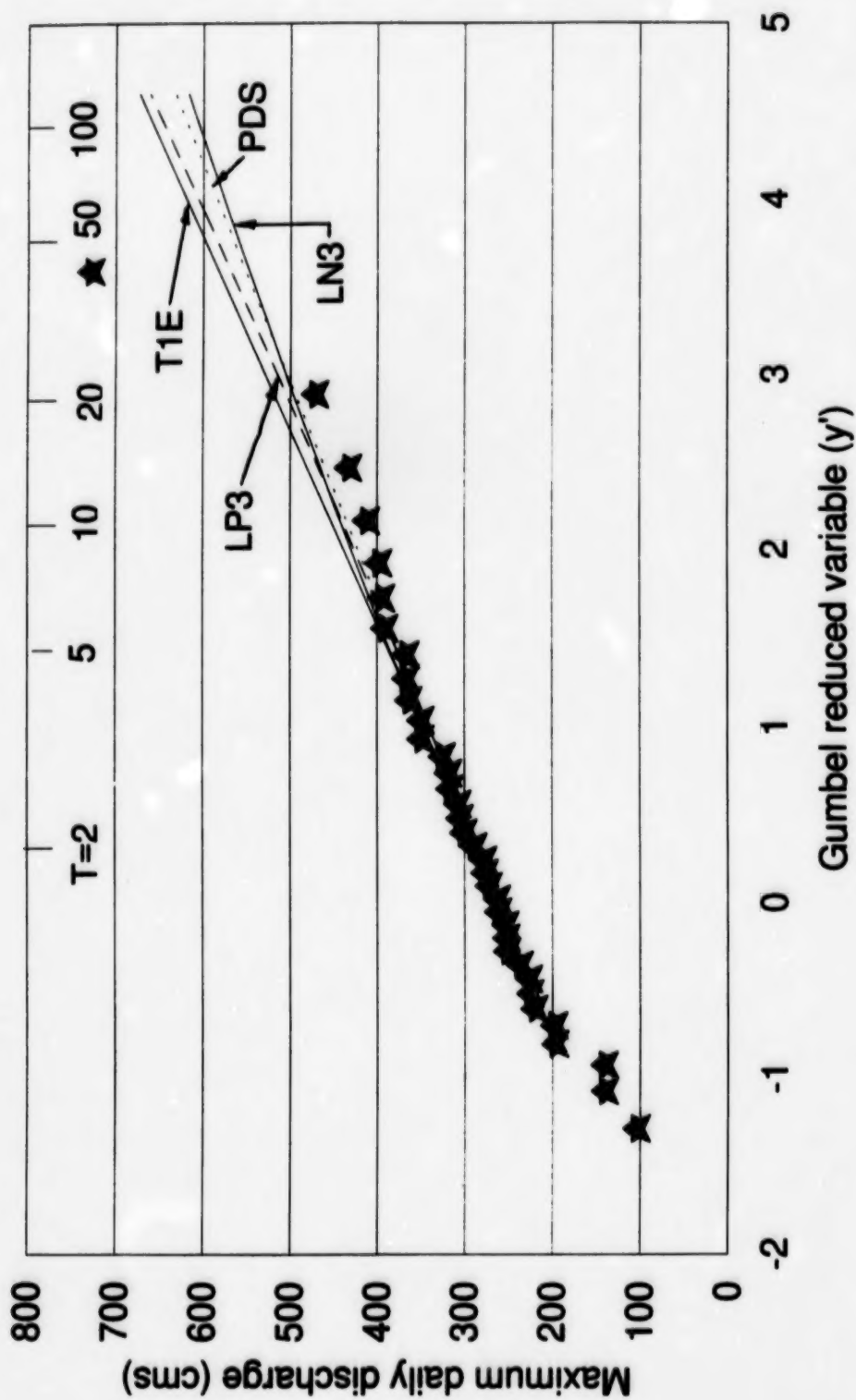


Figure 4. Flood frequency analysis of the Petitcodiac River. LN3 = Lognormal 3P
 T1E = Type 1 Extremal; LP3 = Log-Pearson III; PDS = Partial Duration Series

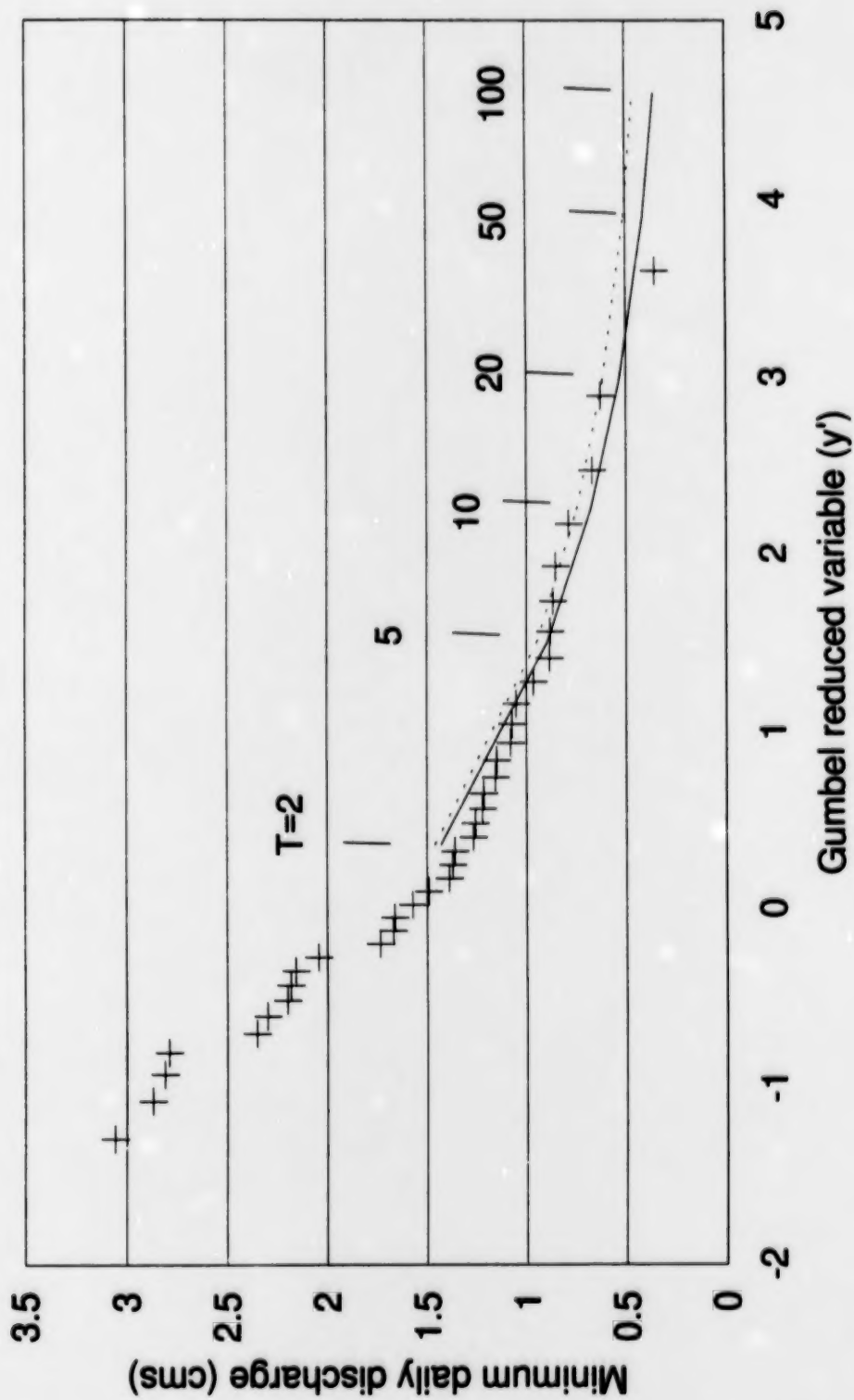


Figure 5. Low flow frequency analysis of the Petitcodiac River for different recurrence intervals (T). (solid line includes 1966 low flow while dashed line excludes 1966).

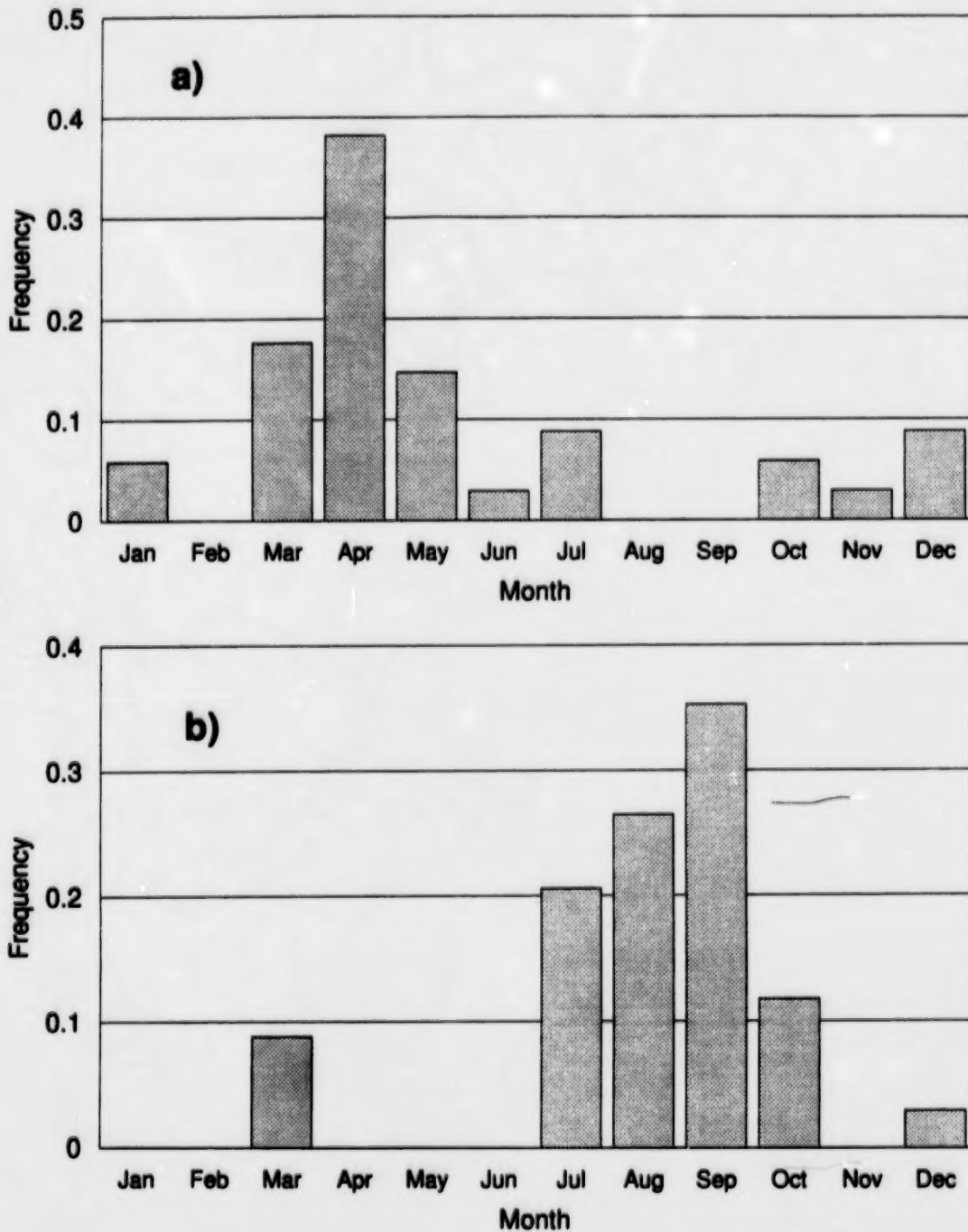


Figure 6. Frequency of a) high and b) low flows by month for the Petitcodiac River

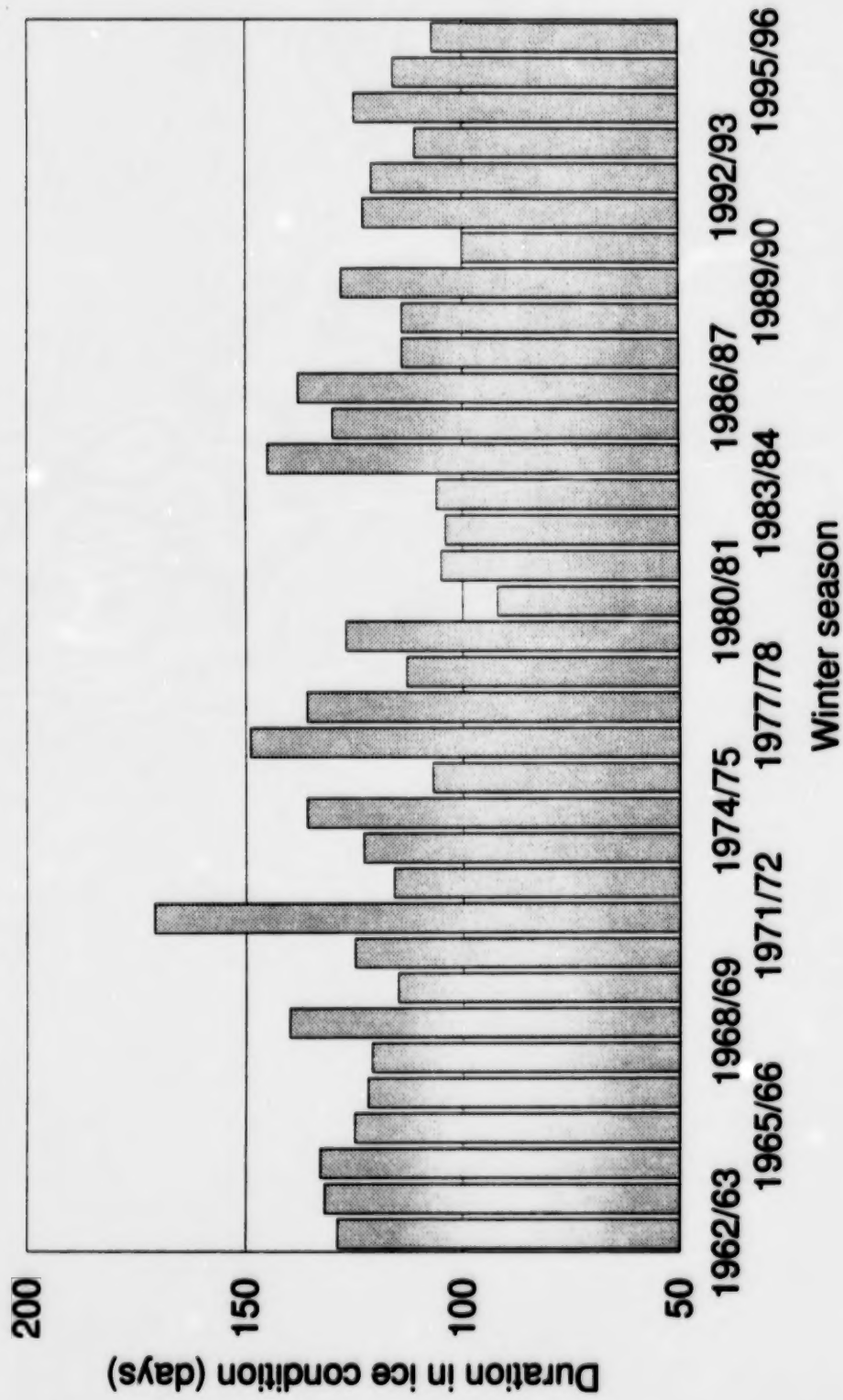


Figure 7. Duration of river ice condition (ice cover) in the Petitcodiac River

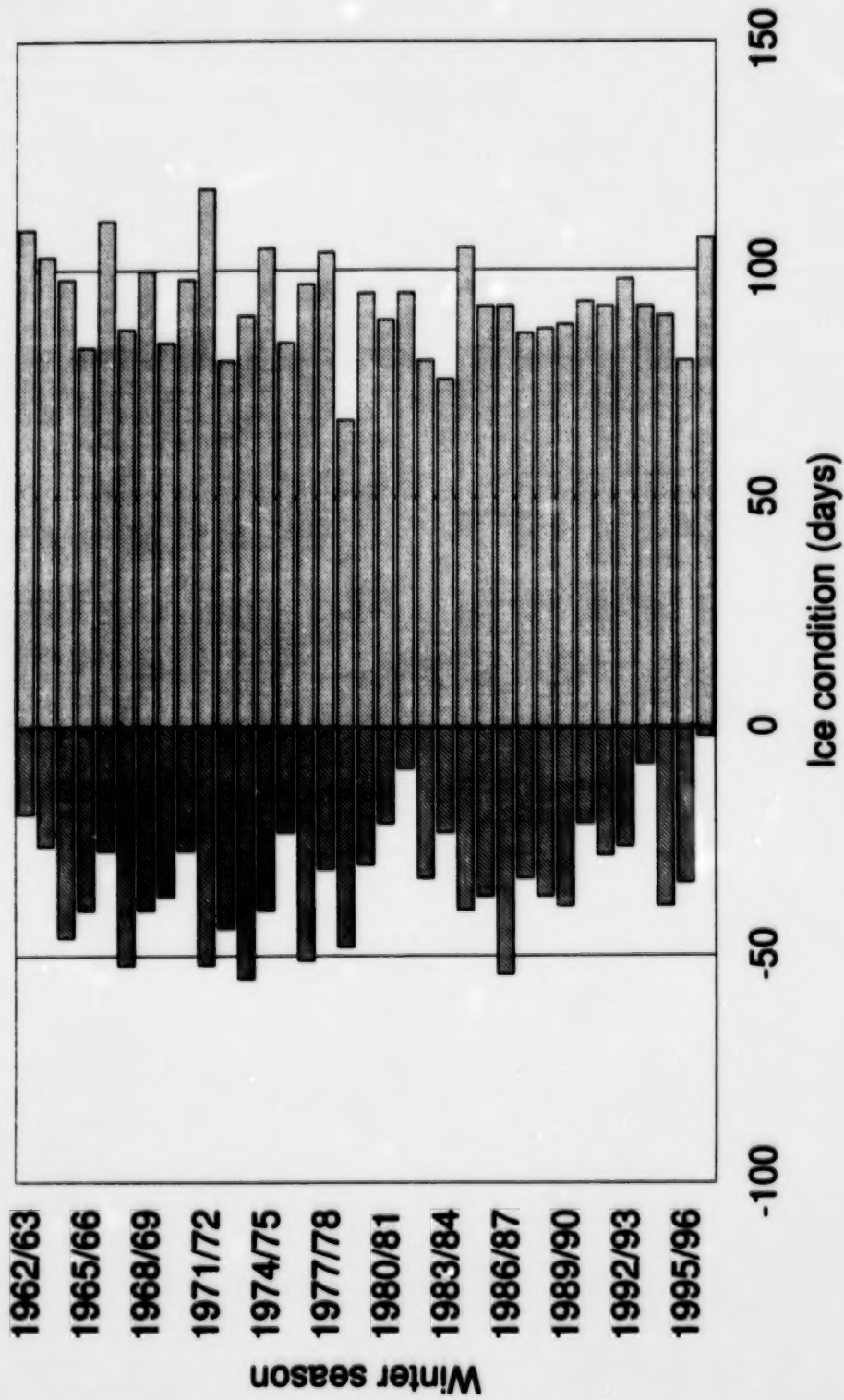


Figure 8. Period of ice cover (start to end) in the Petitcodiac River
(day -50 = Nov. 11; day +50 = Feb. 19; and day +100 = Apr. 10)

Appendix A

Grubbs and Beck Outlier test

Time series may have outliers, which means that certain observations are abnormally high or low compared to the bulk of the data. The occurrence of outliers in time series can greatly influence the results of further analyses, and it is therefore imperative to identify their presence. For instance, in high or low flow frequency analyses, outliers can influence on the magnitude of higher return floods or low flows. The problem in how to treat the presence of outliers in time series remains part of much discussion in hydrology today. Many argues that outliers should be removed from the analysis because they do not represent the norm, while others argue that they should remain part of the analysis because they represent a relevant and important data point. The inclusion or exclusion of outliers obviously will depend on the objective of the analysis.

Many procedures have been used to identify outliers in time series (Bobee and Ashkar 1991), and the one presented here will be the Grubbs and Beck outlier test (Grubbs and Beck 1972).

In the application of such test, the assumption was made that the logarithms of data points (or other function of the hydrologic time series) are normally distributed.

The upper and lower limits are calculated by:

$$[A.1] \quad X_H = \exp(\bar{x} + K_N s)$$

$$[A.2] \quad X_L = \exp(\bar{x} - K_N s)$$

Where \bar{x} and s represent the mean and standard deviation of the natural logarithms of the sample data points. K_N is the Grubbs and Beck statistic, which is a function of sample size and significance levels (Grubbs and Beck 1972). For a 10 % significance level, K_N can be obtained by the following polynomial approximation (Pilon et al 1985):

$$[A.3] \quad K_N \cong -3.62201 + 6.28446N^{1/4} - 2.49835N^{1/2} + 0.491436N^{3/4} - 0.037911N$$

where N is the sample size. Data points which are higher than X_H and lower that X_L are considered outliers by the Grubbs and Beck test.

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Table A.1 Values of K_N in the application of the Grubbs and Beck test for different sample sizes (N) at a significance level of 10%.

N	K_N	N	K_N
1	0.618	16	2.278
2	1.069	17	2.308
3	1.328	18	2.335
4	1.507	19	2.361
5	1.643	20	2.385
6	1.751	25	2.485
7	1.840	30	2.564
8	1.915	35	2.628
9	1.980	40	2.682
10	2.037	45	2.728
11	2.088	50	2.768
12	2.134	55	2.804
13	2.175	60	2.836
14	2.212	65	2.866
15	2.247	70	2.892